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Statistical Modeling of Surface Roughness produced by Wet turning using soluble oil-water mixture lubricant

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***Abstract*- Machining tests were carried out by turning En-31steel alloy with tungsten carbide tools using soluble oil-water mixture lubricant under different machining conditions. First-order and second-order surface roughness predicting models were developed by using the experimental data by applying response surface methodology and factorial design of experiments. The established equations show that the feed rate is the main influencing factor on the surface roughness followed by tool nose radius and depth of cut. It increases with increase in the feed rate but decreases with increase in the cutting velocity and tool nose radius, respectively. The predicted surface roughness values of the samples have been found to lie close to that of the experimentally observed values. There is an improvement in surface finish by 10% with wet machining as compared to dry machining.**

***Keywords:* Response surface method, surface roughness, metal cutting, factorial design**

I. INTRODUCTION

Surface roughness determines how a real object interacts with its environment. Rough surfaces usually wear more quickly and have high friction coefficient than smooth surfaces. Roughness is often a good predictor of the performance of mechanical components, since irregularities in the surface may form nucleation sites for cracks or corrosion. Although roughness is usually undesirable, it is difficult and expensive to control in manufacturing. Decreasing the roughness of surface will usually increase its metal cutting costs exponentially. A proper combination of cutting conditions is extremely important because this determines surface quality of manufactured parts. The growing demand for higher productivity, product quality and overall economy in manufacturing by machining and grinding, insists high material removal rate and high stability and long life of the cutting tools. But machining and grinding with high cutting velocity, feed rate and depth of cut is inherently associated with generation of large amount of heat and high cutting temperature. Such high cutting temperature not only reduces dimensional accuracy and tool life but also impairs the surface integrity of the product by inducing tensile residual stresses, surface and subsurface micro-cracks in addition to rapid oxidation and corrosion [1]. The cutting fluids serve many useful functions including, cooling of the cutting tool at higher speeds, lubricating at low speeds and high loads, increasing tool life, improving the surface finish, reducing the distortion due to temperature rise in the work piece, facilitating chip handling and disposal, providing a protective layer on the machined surface from oxidation and protecting the machine tool components from rust. A recent investigation performed by Alauddin et al [2] has revealed that when the cutting speed is increased, productivity can be maximized and surface quality can be improved. U.M. Shirsat and B.B. Ahuja [3] studied the influence of burnishing parameters on surface finish. The finishing parameters considered were speed, feed rate, burnishing force. It was found that the surface roughness improves initially with an increase in these parameters. After a certain stage, the surface finish deteriorates and fatigue life decreases. According to Hasegawa et.al.[4], surface finish is characterized by various parameters such as average roughness (Ra), smoothening depth (Rp), root mean square (Rq) and maximum peak to valley height (R_t).This study used average roughness for the characterization of surface finish, since it is widely used in metal cutting industry. Bar die [5] developed a surface roughness model for gray C.I. (154 BHN) using carbide tool under dry conditions turning and for constant depth of cut. Dilbag Singh and P.V. Rao [6] developed a surface roughness prediction model for hard turning process, using mixed ceramic inserts (turning) having different nose radii and different rake angles, of the cutting tools. They found that the feed rate is the dominant factor determining the surface finish followed by nose radius and cutting velocity. Sundaram and Lambert [7] developed the mathematical models for predicting the surface roughness of AISI 4140 steel during the fine turning operation using both Tic coated and uncoated tungsten carbide throw away tools. The parameters considered were cutting speed, feed rate, depth of cut, nose radius and type of the tool .Bardie [8], Mital and Mehta [9] conducted a survey of surface prediction models developed and factors influencing the surface and developed the surface finish models for aluminum alloy 390, ductile cast iron, medium carbon leaded steel, medium carbon alloy steel 4130, and inconel 718 for a wide range of machining conditions defined by cutting speed, feed rate and tool nose radius. They reported that statistical analysis of experimental data indicated that the surface finish is strongly influenced by the type of the metal, cutting speed, feed rate and tool nose radius. The depth of cut was kept constant throughout the experiment

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While the effects of feed rate and the tool nose radius on surface finish were generally consistent for all materials, the effect of cutting speed was not. Kopac et al. [10] investigated the use of response surface methodology (RSM) in developing a surface roughness prediction model. Petropoulos [11] found through statistical analysis a pronounced effect of tool wear on the Ra and Rmax, values of surface roughness. Paulo [12] studied the influence of cutting conditions on the surface finish obtained by turning, using the Taguchi techniques. Bandyopadhyay [13] have shown that by increasing the cutting speed, the productivity can be maximized and at the same time, the surface quality can be improved. According to Gorlenko [14] and Thomas [15], surface finish can be characterized by various parameters. They suggested that numerous roughness height parameters such as average roughness, root mean square and maximum peak to valley height can be closely correlated. The present study uses average roughness for the characterization of surface roughness due to the fact that it is widely adopted in the industry for specifying the surface roughness. Benga and Abrao [16] investigated the effect of speed and feed rate on surface roughness and tool life using three level factorial design on machining of hardened 100cr6 bearing steel (62-64 HRC) using ceramic and CBN tools. They found that the feed rate is most significant factor affecting surface finish and cutting speed has very little influence on surface finish with both ceramic and CBN cutting tools. EI-Wardany et al.[17] investigated experimentally the effect of cutting parameters and tool wear on chip morphology and surface integrity during high speed machining of D2 tool steel (60-62HRC) using CBN tool. A.R. Machado et.al [18] studied analysis of various cutting fluids when turning AISI8640 steel with triple coated carbide tools and showed that the use of synthetic and semi synthetic fluids gave longer tool life than emulsions of mineral oils or when machining dry.Bardie [19] showed that effective use of cutting fluids can improve the surface finish of the product.Adoslav Raki and Zalata Raki [20] studied the influence of cutting fluids on the failure of machine tools. The investigations were carried out on 30 lathes in four different time periods. The obtained results indicated that water based metal working fluids have a great influence on tribological process, wear and failures of tribo- mechanical system. Wang and kou [21] studied the effectiveness of cutting fluids as a coolant in grinding. The results reveal that water has higher cooling effectiveness than oil. In addition, the cooling effect of the grinding fluid becomes more significant at lower workpiece speed, higher grinding depth and greater wheel speed. Abhang and Hameedullah [22] developed surface roughness prediction model for alloy steel turned with tungsten carbide tool under dry cutting. They concluded that the feed rate and depth of cut are the dominant factors determining the surface finish followed by tool-nose radius and cutting speed [22]. In the present study experimental investigation are conducted by turning En-31 steel alloy with tungsten carbide cutting tool using soluble oil-water mixture lubricant under different conditions of cutting speed, feed rate, depth of cut and tool nose radius. Surface roughness values are recorded and statistically analyzed by Minitab software. First and second- order surface roughness prediction models are developed and reported.

II. RESPONSE SURFACE METHOD

Factorial designs are used widely in experiments involving several factors on a response. The meaning of factorial design is that each complete test or replications of all the possible combinations of the levels of the factors are investigated [8]. Factorial design with eight added centre points (2^4+8) used in this work is a composite design [23]. The proposed linear model correlating the responses and independent variable can be represented by the following equation.

Y = m* (cutting speed) + n*(feed rate) + p *(depth of cut) +q*(tool nose radius) +e (1)

Where, Y is the response, e, m, n, p and q are the constants. Equation (1) can be written in the following form.

$$Y = \varnothing (v, f, d, r) + \in \qquad (2)$$

$$Y_1 = \beta_o X_o + \beta_1 X_1 + \beta_2 X_3 + \beta_4 X_4 \qquad (3)$$

Where Y_1 is the response, $X_o = 1$ (dummy variables),

X_1 = cutting speed, X_2 = feed rate, X_3 = depth of cut and X_4 = tool nose radius,

β_o = c and $\beta_{1, 2, 3}$ and $_4$ are the model parameters.

The general second order model can be expressed as equation (4)

$$Y_2 = {}_oX_o + {}_1X_1 + {}_2X_2 + {}_3X_3 + B_4X_4 + {}_{12}X_1X_2 + {}_{23}X_2X_3 + {}_{14}X_1X_4 + {}_{24}X_2X_4 + {}_{13}X_1X_3 + {}_{34}X_3X_4 + {}_{11}X_1^2 + {}_{22}X_2^2 + {}_{33}X_3^2 + {}_{44}X_4^2 \qquad (4)$$

Where, Y_2 is the estimated response based on second order equation. The parameters $_o$, $_1$, $_2$, $_4$, $_{12}$, $_{23}$ and $_{14}$, are to be calculated by the method of least squares. The basic formula is

$$=(X^TX)^{-1}X^{T.}Y \qquad (5)$$

Where the calculation matrix X and the variance matrix $(X^T.X)^{-1}$. Hence the β values can be determined by using eqn. (5).

III. EXPERIMENTAL SET-UP AND CUTTING CONDITIONS

The experiments are carried out on HMT heavy duty lathe machine [LTM-20]. Soluble oil (Koolkut-40, a product of Hindustan petroleum, emulsified oil, emulsion strength 5-10 % with water in the ratio of 1:20) coolant was used in this experiment. Water was added into the coolant until the mixture of coolant and water reached the pH ranges from 9.0 to 9.5. Commercial alloy steel work-piece (EN-31) is machined on HMT lathe. Table1andTable2 shows three levels of factors and chemical composition of work piece material respectively. Each experiment was repeated three times using new cutting tool every times to obtain accurate readings of the surface roughness. The averages of three readings of surface roughness values have been recorded.

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The work piece material used has a dimension of 600 mm in length and 50 mm in diameter. The cutting tool holder used for turning operation is WIDAX tool holder SCLCR 12.12 Fog 13 and diamond shape carbide insert (CNMA 1204-04, CNMA 120408 and CNMA 1204 12). [$\alpha = 6^o$, $V_o = -6^o$, $\lambda = -6^o$, Kr = 95^o, $\in$ r = 80^o, r = 0.4, 08, 1.2mm].
This method classifies and identifies the parameters at three different levels (i.e. low, middle and high) as shown in table1.The process variables or control variables such as cutting speed , feed rate, depth of cut and tool nose radius are identified to carry out the experiments and to develop the statistical empirical models. In this investigation the surface roughness was measured on an optical microscope (Carl-zesis, Japan made lens factor is 0.89). The surface roughness was taken perpendicular to the turning direction. In this work the centre line average surface roughness (Ra) values were measured by taking average of the three readings.

TABLE I:
THREE LEVELS OF VARIABLES AND CODING IDENTIFICATION.

Levels	V m/min	F mm/rev	D mm	R mm	X_1	X_2	X_3	X_4
Low	39	0.06	0.2	0.4	-1	-1	-1	-1
medium	112	0.10	0.4	0.8	0	0	0	0
high	189	0.15	0.6	1.2	+1	+1	+1	+1

X_1= cutting velocity, X_2= feed rate, X_3= depth of cut and X_4= nose radius.

TABLE II:
CHEMICAL COMPOSITION OF ALLOY STEEL [EN-31] WORK PIECE

Comp'	C	Si	Mn	Cr.	Co	S	P
Wt. %	0.95-	0.10 -	0.30	1.0-	0.025	0.040	0.040

IV. RESULTS AND DISCUSSION

This research is conducted with two purposes. The first was to demonstrate the use of response surface methodology and design of experiments in order to identify the optimum surface roughness, with particular combination of cutting parameters and tool geometry (tool nose radius). The second was to demonstrate a systematic procedure for using factorial design of experiments with RSM in process design of turning operations. The effect of tool nose radius was also considered apart from the effects of the process parameters on the surface roughness. A factorial design with eight added centre points is sufficient to investigate the main and interaction effects on surface roughness. The first order and second order equation developed to predict the surface roughness are given in equation (6) and (7).

Ra_1=8.4288 - 0.0005V + 29.7560 F + 2.6656D - 0.4359R (6)

where V, F, D and R are the cutting speed, feed rate, depth of cut and tool nose radius respectively. Equation (6) shows that the surface roughness increases with increase of feed rate and depth of cut but decreased with cutting speed and tool nose radius. The feed rate has the most dominant effect on surface roughness value produced by tungsten carbide tools. The major effect on the surface roughness is due to the feed rate. Hence smaller values of feed rate and depth of cut must be selected in order to achieve better surface finish during steel turning operation.

R_{a2} = 5.48 - 0.0070 V + 58.0 F + 10.2 D+ 0.04 R + 0.0076 VF - 61.5 FD + 0.00096 VR - 5.7 FR - 0.0103 VD +0.05DR+0.000040V^2 (7)

By examining the coefficients of the second order terms, it can be seen that the feed rate has the most dominant effect on the surface roughness. After examining the experimental data, it can be seen that the contribution of cutting speed is the least significant. Also, because the P-value of interaction and square terms are 0.412 and 0.574(e" 0.05), one can easily deduce that the interactions and square terms of distinct design variables are less significant at 95% confidence level except F*D and F*R. They improve the surface finish. As seen from fig.3, the predicted surface roughness using the second order RSM model closely match with the experimental results. It exhibits the better agreement as compared to those from the first-order RSM mode. The analysis of variance and the F ratio test have been performed to justify fitness of the mathematical model. The F- ratio of the predictive model is calculated and compared with the standard tabulated value of the F-ratio for a specific level of confidence. The adequacy of the first and second order model was verified using the analysis of variance (ANOVA) as shown in Table 4 and Table 5. At a level of confidence of 95.00%, the model was checked for its adequacy. As shown in table 4 and 5, P value of first-order model is 0.91 and the second-order model is 0.982. Because these values are greater than 0.05 the lack-of fit is not significant for both the models that means the fit is significant and the models are adequate [23].

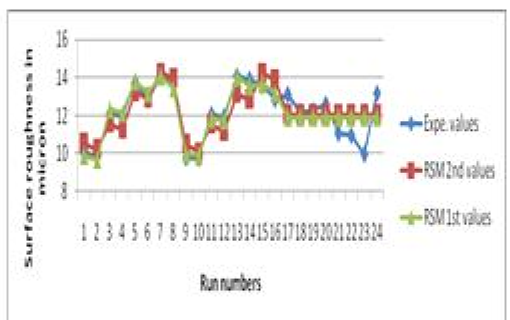

Fig .3: Comparison between the Experimental and Predicted values of Surface Roughness

The results show that the cutting speed has lesser impact on surface roughness in the studied range. This observation is in agreement with the findings of previous researchers Benga and Abrao [16], EI-Wardany et.al [17] and Abhang and Hameedullah [22]. Therefore higher cutting speed could be used to improve the productivity. The result for analysis of variance for the second order model reveals that the interaction terms and the square terms are statistically less significant at 95% confidence level. They have smaller effect on surface roughness. This observation is in agreement with

the findings of dry machining [22]. The wet machining results in 5-10% lower surface roughness values, as compared to dry machining for similar cutting conditions [22]. During wet machining surface roughness is improved by reducing the cutting forces and tool wear rate as well as increasing heat transfer rate as compared to dry machining. The significance of the effect of cutting fluids agrees with the results of Adoslav Raki et al, [20], and Wang et al. [21]. Soluble oil-water mixture lubricant provides good lubrication and cooling action between tool-chip and chip-workpiece interface during machining that leads to improved surface finish. The developed equations clearly show that the feed rate is the most influencing factor on surface roughness followed by tool nose radius and depth of cut. This is in agreement with the work of Benga and Abrao [16] .The increase in feed rate increases surface roughness, but decreases with increasing cutting velocity and tool nose radius. During machining, if feed rate is increased, the normal load on the tool also increases and it will generate heat which in turn increases the surface roughness. This is anticipated as it is well known that for a given tool nose radius, the theoretical surface roughness is generally ($Ra = f^2 / (32*r)$) (7). Thus, with increase in depth of cut, the surface roughness value increases, because with increase in depth of cut chatter may result causing degradation of the work piece surface and larger tool nose radius reduces surface roughness. The surface roughness values obtained by using insert radius of 1.2mm were less than the surface roughness values obtained by using the insert radii of 0.8mm and 0.4mm .The reason for obtaining better surface quality with in insert radius of 1.2mm than with the other two inserts may be ascribed to the form of better roundness of this insert than the other two. This result agrees with [22].

TABLE III:
ANALYSIS OF VARIANCE FOR FIRST ORDER EQUATION

Source	D.F	S.S.	M.S.	F-value	P-value
Regression	4	33.863	8.4659	10.30	0.000
Linear	4	33.863	8.4659	10.30	0.000
Res error	19	15.613	0.8217	-	-
Lack-of fit	12	6.542	0.5452	0.42	0.910 ns
Pure error	7	9.07	-	-	-
Total	23	49.417	-	-	-

D.F= degrees of freedom, SS= sum of squares, M.S= mean square.Ns= not significant

TABLE IV:
ANALYSIS OF VARIANCE FOR QUADRATIC EQUATION

Source	D.F	S.S.	M.S.	F-value	P-value
Regression	11	39.6872	3.6079	4.39	0.009
Linear	4	33.8634	3.5678	4.34	0.021
Square	01	0.2752	0.2753	0.33	0.574
Interaction	6	5.4688	0.9115	1.11	0.412
Res error	12	9.8686	0.8224	-	-
Lack-of fit	5	0.7983	0.1597	0.12	0.983 ns
Pure error	7	9.0703	1.2958	-	-
Total	23	49.4760	-	-	-

D.F= Degrees of freedom, SS= Sum of squares, M.S. = Mean square, Ns= not significant

V. CONCLUSION

1) Response surface methodology combined with the factorial design of experiment is found to be a successful technique to perform trend analysis of surface roughness with respect to various combinations of design variables (metal cutting velocity, feed rate, depth of cut and tool nose radius).

2) The first order and second-order mathematical models are found to adequately represent the surface roughness.

3) The surface roughness increases with increase in feed rate followed by depth of cut but decreases with increase in the cutting velocity and tool nose radius respectively.

4) The first order and second order models developed in the research produce smaller errors and have satisfactory results. Therefore the proposed model can be used to predict the corresponding roughness of EN-31 steel at different parameters in turning.

5) With the model equations obtained, a designer can subsequently select the best combination of design variables for achieving optimum or minimum surface roughness during steel turning process. This eventually reduces the machining time, operation efforts, cost and save the cutting tools. A good combination among the cutting speed, feed rate, depth of cut and tool nose radius can provide better surface quality.

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